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6. AUTHORS
Youqi Wang, Xiaojiang Jack Xin

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Kansas State University
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Kansas State University
Manhattan, KS 66506 -

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14. ABSTRACT
Fabric systems with through-the-thickness reinforcement have better ballistic strength than those without it. The focus of the current project is to develop the computational capability to evaluate multilayer fabric systems with through-the thickness reinforcement as well as its failure mechanism after ballistic impact. In this project, a numerical model has been established to generate the micro-geometry of fabrics fabricated using TexTech needle-punching technology. A hybrid mesh model has been developed which produces results close to those

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Ballistic impact, multi-layer fabric, through-the-thickness reinforcement, 2-D woven fabric, barbed needle punch process, TexTech core matrix technology, uniform mesh, hybrid mesh, yarn stress, fabric deformation

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Report Title

Final Report: Ballistic Strength of Multi-Layer Fabric System with Through-The-Thickness Reinforcement

ABSTRACT

Fabric systems with through-the-thickness reinforcement have better ballistic strength than those without it. The focus of the current project is to develop the computational capability to evaluate multilayer fabric systems with through-the thickness reinforcement as well as its failure mechanism after ballistic impact. In this project, a numerical model has been established to generate the micro-geometry of fabrics fabricated using TexTech needle-punching technology. A hybrid mesh model has been developed which produces results close to those obtained using full field uniform mesh and yet uses less computer resource by a factor of ten or more. Furthermore, a post-processor has been developed which can display the ballistic perforation process step by step and enables the analysis of the fabric failure mechanism. Based on the work accomplished, we have established the capacity to (1) simulate the fabrication procedure of needle-punching the through-the-thickness fibers into multi-layer fabric systems, (2) conduct ballistic simulations of the TexTech fabric systems with various layer configurations, (3) compare numerical ballistic simulation results to experimental results, and (4) provide information for optimal hybrid design of multilayer fabric systems with through-the-thickness reinforcement.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Ying Ma	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Youqi Wang	0.50	
Xiaojiang Jack Xin	0.50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

BALLISTIC STRENGTH OF MULTI-LAYER FABRIC SYSTEM WITH THROUGH-THE-THICKNESS REINFORCEMENT

Final Report Submitted to Army Research Office
7 Months FY-12-FY13, STIR Program, $50K

Youqi Wang and Xiaojiang Jack Xin
Department of Mechanical and Nuclear Engineering
Kansas State University
Manhattan, KS 66506

Keywords: Ballistic impact, multi-layer fabric, through-the-thickness reinforcement, 2-D woven fabric, barbed needle punch process, TexTech core matrix technology, uniform mesh, hybrid mesh, yarn stress, fabric deformation

ABSTRCT

Fabric systems with through-the-thickness reinforcement have better ballistic strength than those without it. The focus of the current project is to develop the computational capability to evaluate multilayer fabric systems with through-the thickness reinforcement as well as its failure mechanism after ballistic impact. In this project, a numerical model has been established to generate the micro-geometry of fabrics fabricated using TexTech needle-punching technology. A hybrid mesh model has been developed which produces results close to those obtained using full field uniform mesh and yet uses less computer resource by a factor of ten or more. Furthermore, a post-processor has been developed which can display the ballistic perforation process step by step and enables the analysis of the fabric failure mechanism. Based on the work accomplished, we have established the capacity to (1) simulate the fabrication procedure of needle-punching the through-the-thickness fibers into multi-layer fabric systems, (2) conduct ballistic simulations of the TexTech fabric systems with various layer configurations, (3) compare numerical ballistic simulation results to experimental results, and (4) provide information for optimal hybrid design of multilayer fabric systems with through-the-thickness reinforcement.

1. INTRODUCTION

Multi-layer 2-D woven ballistic fabrics are used as soft armor for soldier protection. Recently, TexTech has employed a non-aggressive needle punch process to insert through-the-thickness reinforcement into multi-layer fabric systems. The through-the-thickness reinforcement increases the interaction between layers and changes the deformation pattern during the ballistic perforation process. Experimental results show that fabric systems with through-the-thickness reinforcement have better ballistic strength than those without it. The objective of this project is

to develop the computational capability to evaluate multilayer fabric systems with through-the thickness reinforcement as well as its failure mechanism after ballistic impact.

The scientific challenges of the project include 1) to understand the micro-geometry of the TexTech fabric system, 2) to develop a computer tool using a filament-level micro-mechanics model capable of analyzing a 10-20 layer fabric system within a reasonable amount of computer time and 3) to observe the step-by-step failure process after ballistic impact.

In recent years, Kansas State University has collaborated with the Army Research Laboratory (ARL) to develop a parallel code that simulates the ballistic penetration process through fabrics. The code has been used for ballistic impact simulation through the single layer 2-D woven fabric. The efficiency of the numerical tool must be improved in order to use it to simulate the penetration process of the multi-layer fabric. A post-processor must also be incorporated into the numerical tool to process the parallel simulation. An efficient computer tool and a post-processor are important not only for this project, but also for another research effort sponsored by ARL. Under the auspices of ARL, we have developed both a hybrid digital element mesh approach to improve the efficiency of the computer code and a post-processor capable of processing data generated by a parallel code.

2. RESEARCH ACTIVITIES

2.1 Collaboration with TexTech

The Kansas State University research group and the ARL project contact person, Dr. Chian Fong Yen, visited TexTech in fall 2012. TexTech produces the multi-layer fabric system that utilizes a non-aggressive barbed needle punch process, named "TexTech core matrix technology". Through-the-thickness reinforcement increases the interaction between layers and changes the profile pattern. TexTech provided detailed information about the manufacturing process of the fabric.

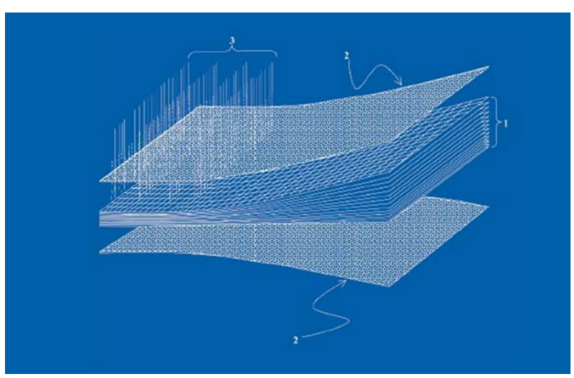


Figure 1 TexTech core matrix technology

Figure **1** illustrates the TexTech core matrix technology. The fabric includes three parts: surface layers, core layers and through-the-thickness reinforcement. The surface layers consist of ballistic grade fiber battings, which are fabricated from randomly distributed continuum fibers through a batting process. The core layers are 2-D woven Twaron fabrics. Z-direction fibers are inserted using non-aggressive barbed needles. Generally speaking, the ballistic strength is related to the fabric count and the inter-yarn space. Ballistic fabric often has a high yarn count and a small inter-yarn space so as to prevent the lateral movement of principal yarns near the ballistic impact center. In Textech's multi-layer system, z-direction through-the-thickness fibers inhibit lateral movement of the principal yarns. Therefore, a relatively coarse 2-D woven fabric can be employed to reduce cost.

Kansas State University already has the capability to generate various 2-D woven fabrics. Based upon the visit, a numerical model has been designed to generate the batting layers.

A batting layer composed of randomly distributed fibers can be generated by a random walk. A continuum fiber can be created by the random walk process shown in Figure 2. Assume that there are N fibers in a unit cell. N starting nodes are randomly distributed within the unit cell. The second node of each fiber is randomly located in a spherical shell of inner radius l_{min} and outer radius l_{max}. Similarly, the third and fourth nodes can be created. The process continues until a fiber with a pre-assigned length is generated. An excluded volume condition is imposed at each step, i.e., two nodes from two different fibers cannot occupy the same space. In addition, a periodic boundary condition is applied when the fiber reaches the unit-cell boundary. Then the unit cells are relaxed under compressive force in the z-direction.

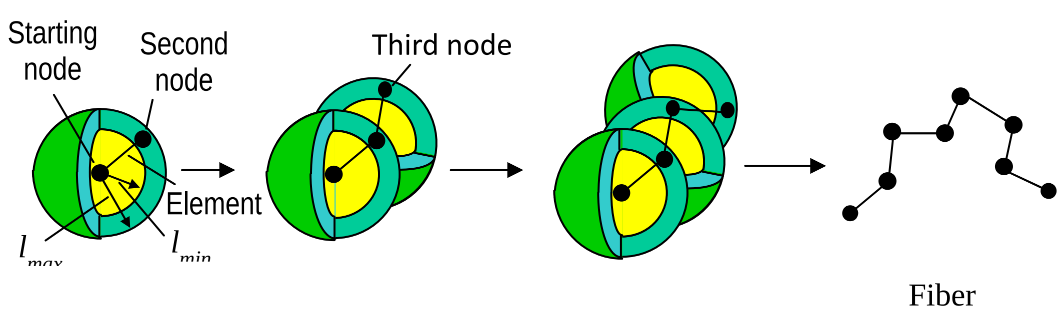


Figure 2 Generation of a randomly distributed fiber

The punch process is modeled as a two-step process. In the first step, the punch point is selected based on needle distribution. The second step is to find a node close to the punch point. Imitating the punch process, the fiber is pushed downward through the core, which is composed of multi-layer 2-D woven fabrics. As such, a material unit cell can be generated.

2.2 Hybrid Mesh

The current computer code developed at Kansas State University can only simulate single layer fabrics up to 10 inches. A hybrid mesh approach has consequently been developed to improve simulation capacity. A hybrid mesh of a 4" square fabric is shown in Figure 3. The blue yarns are composed of 19 digital fibers and the green yarns of four digital fibers. The preliminary numerical simulation comparison is shown in Figure **4**. In Figure **4**-a, a 16 grain RCC projectile is applied with a 150m/s strike velocity; in Figure **4**-b, a 4 grain RCC projectile is applied with a 300m/s strike velocity. The horizontal axis represents elapsed time after impact and the vertical axis represents the reaction force applied to the projectile by the fabric. The results are close. Therefore, in numerical simulation, replacement of the full field uniform mesh by the hybrid mesh looks plausible. For a 12 inch fabric, the hybrid mesh consists of less than 10% of the nodes or element of a full field uniform mesh. Therefore, the simulation is 10 times more efficient. Based on current capability at Kansas State University, we are able to simulate the standard ballistic tests of TexTech fabrics in reasonable computing time.

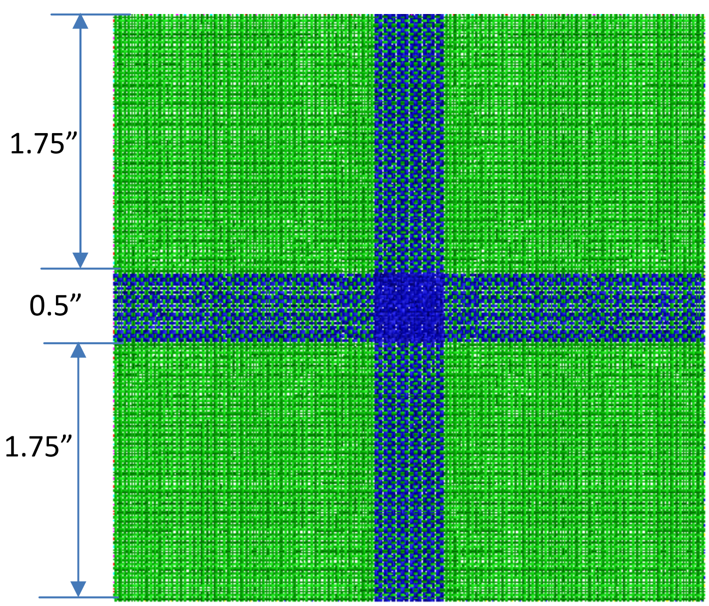
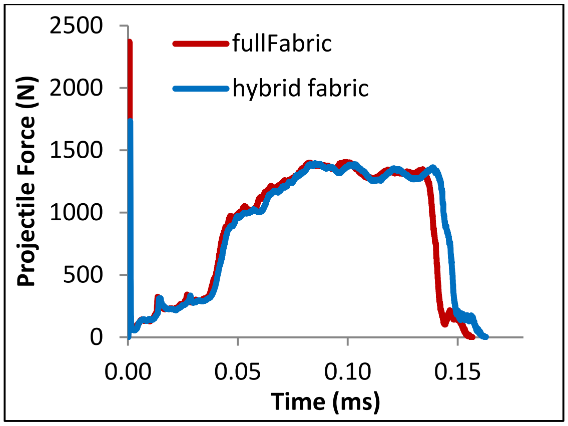
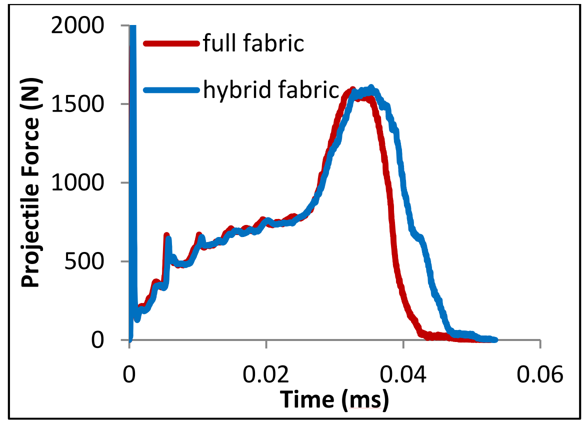


Figure 3 Hybrid Mesh



(a) 16g RCC Projectile, V_s = 150m



(b) 4 g RCC projectile, V_s = 300m/s

Figure 4 Comparison between uniform mesh simulation and hybrid mesh simulation

2.3 Post-Processor

To analyze the failure mechanism of the TexTech multi-layer fabric with through-the-thickness reinforcement, a post-processor had to be developed in order to process the data generated by the parallel code used in the numerical simulation. During the past seven months, in conjunction with support received from ARL, a post-processor was developed, permitting us to observe fiber and yarn damage step-by-step. Figure **5** is the picture generated by the post-processor, which shows perforation through a 2-D woven Fabric by a projectile. The post-processor also enables generation of yarn stress contours and fabric deformation.

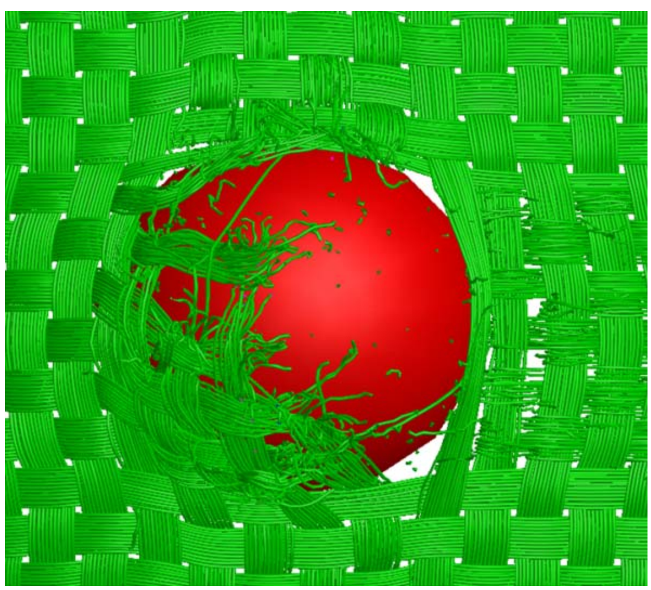


Figure 5 Projectile perforation through a 2-D woven fabric

3. FUTURE EXPLORATION

During the past 7 months, the Kansas State team has:

1. established a numerical model to generate the micro-geometry of fabrics fabricated by TexTech using TexTech core matrix technology.
2. developed a hybrid mesh model. The numerical simulation results derived from the hybrid mesh is compared to results derived from the full field uniform mesh. The numerical results derived from the hybrid mesh are very close to the results derived from the full field uniform mesh. The hybrid mesh model only uses 10% or less computer resource than the full field uniform mesh.
3. developed a postprocessor that can display the ballistic perforation process step by step. This enables us to analyze the fabric failure mechanism.

Based on the work accomplished in this project, we have established the capacity to 1) simulate the fabrication procedure of needle-punching the through-the-thickness fibers into multi-layer fabric systems, 2) conduct ballistic simulations of the TexTech fabric systems with various layer configurations, 3) compare numerical ballistic simulation results to experimental results, and 4) provide information for optimal hybrid design of multilayer fabric systems with through-the-thickness reinforcement. To build on the research results accomplished in this project and further explore the potential of through-the-thickness reinforcement, we plan to submit a proposal to ARO to continue the effort to investigate multi-layer fabric system with through-the-thickness reinforcement and other similar fabric systems.